Raytheon
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26 May 2016

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Contract Number:	N00014-14-C-0002
Proposal Number:	P13003-BBN
Contractor Name and PI:	Raytheon BBN Technologies; Dr. Jonathan Habif
Contractor Address:	10 Moulton Street, Cambridge, MA 02138
Title of the Project:	Seaworthy Quantum Key Distribution Design and Validation (SEAKEY)
Contract Period of Performance (Base + Option):	7 February 2014 – 9 September 2016
Total Contract Amount (Base + Option):	\$475,359 (Base) + \$199,252 (Option)
Amount of Incremental Funds (Base + Option):	\$475,359 (Base) + \$115,189 (Option)
Total Amount Expended (thru 20 May – Base + Option):	\$466,493 (Base) + \$91,729 (Option)

Attention: Dr. Richard Willis
Subject: Quarterly Progress Report
Reference: Exhibit A, CDRLs

In accordance with the reference requirement of the subject contract, Raytheon BBN Technologies (BBN) hereby submits its Quarterly Progress Report. This cover sheet and enclosure have been distributed in accordance with the contract requirements.

Please do not hesitate to contact Dr. Habif at 617.873.5890 (email: jhabif@bbn.com) should you wish to discuss any technical matter related to this report, or contact the undersigned, Ms. Kathryn Carson at 617.873.8144 (email: kcarson@bbn.com) if you would like to discuss this letter or have any other questions.

Sincerely,
Raytheon BBN Technologies

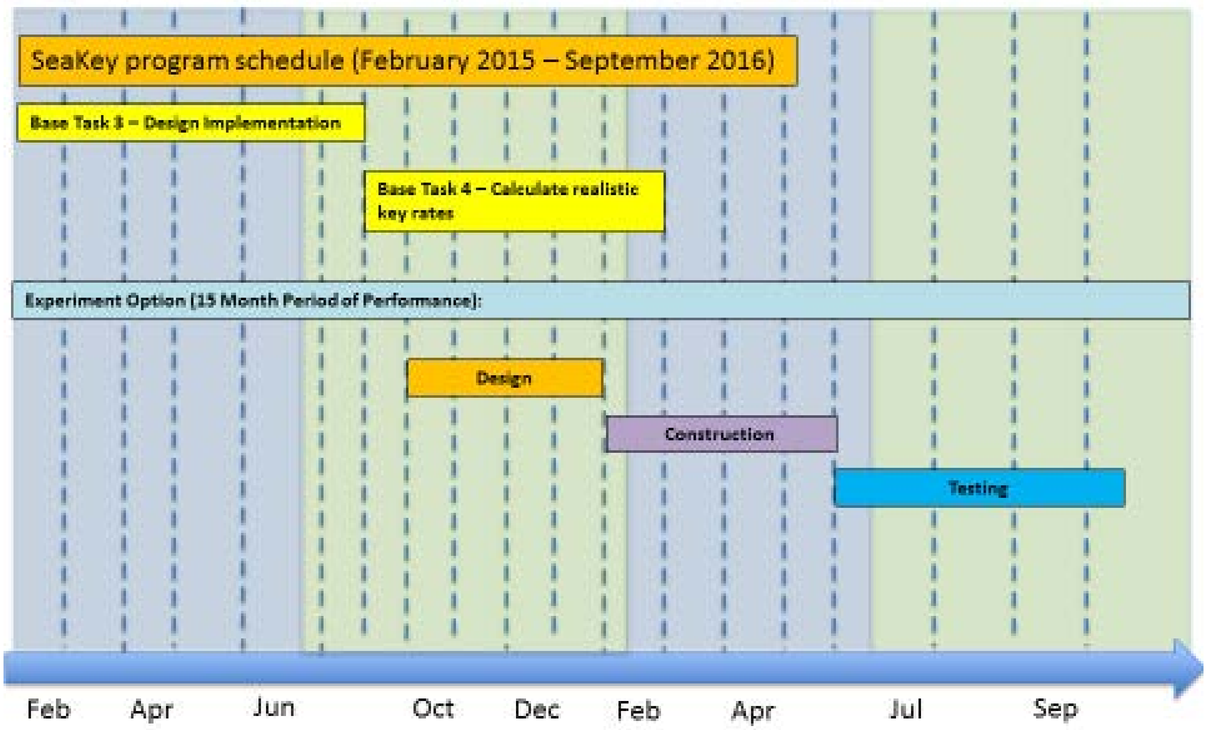
Kathryn Carson

Kathryn Carson
Program Manager
Quantum Information Processing

SEAKEY Quarterly Progress Report for the
Period 23 February 2016 – 26 May 2016 (100 Days)

Section A. Project Schedule

The Year 3 timeline below identifies the high level SeaKey tasks and approximate durations.



Section B. Technical Progress

SUMMARY

In this report we summarize the technical progress accomplished during the first quarter of the third year of the SeaKey program. In this quarter we continued work along the experimental portion of the SeaKey program. The work we have done this quarter continues to evaluate the performance of our homodyne receiver built for decoding phase encoded coherent states. Evaluation by our theorists of the data taken to date has identified excess noise in our receiver, which we spent most of this quarter diagnosing, tracking down and remedying. The progress presented here shows our techniques and efforts to identify and quantify the noise, which we have determined to

come from our laser sources. Finally, we present our path forward in achieving shot noise limited performance for the homodyne receiver, which includes the stable CW local oscillator and balanced detector.

TECHNICAL RESULTS

Our initial aim was to construct the setup shown in Figure 1, and take data of the noise variance of the signal from the balanced detector as a function of local oscillator power. Our first setup used the following equipment described in the following. We also describe the issues we found with each piece of equipment that limited the performance of the receiver from achieving the shot noise limit.

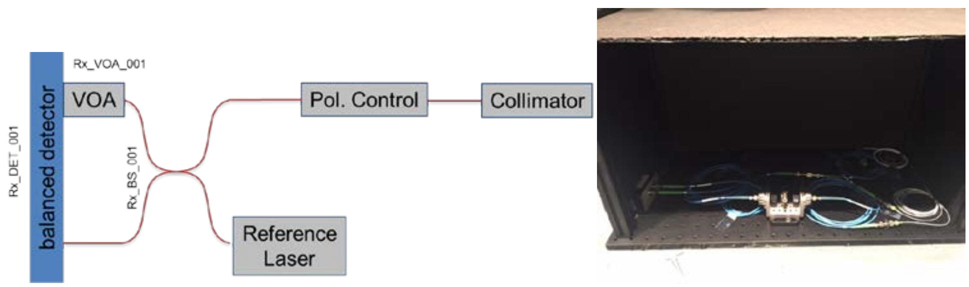


Figure 1 Spiral 2 receiver design (left), following the self-referenced CVQKD proposal. (Right) photograph of the receiver as it currently stands. We have enclosed the receiver in a box to prevent air currents from causing fluctuations in the receiver balancing.

- **Balanced detector**: Thorlabs PDB450C
    - o ***Issue***: This detector had specification for linearity to 5 mW of laser power on each detector of the pair. Upon calling the company, we were informed this was a misprint in the manual and that the actual linearity of the detector was only valid to 1 mW of LO power, therefore any data taken at powers above that were useless.
    - o ***Remedy***: we returned the Thorlabs detector to the vendor, and purchased a new detector from Newport: 1817-FC. We are continuing to evaluate this part
- **Reference Laser:** Orbits Lightwave Ethernal & Santec tunable laser
    - o **Issue:** For both of these lasers we measured excess noise in the balanced homodyne detector beyond what would be expected from shot noise limited relative intensity noise.
    - o ***Remedy*:** We have two remedies for this issue, addressed in further detail below. The first remedy is that we have identified our Ethernal laser operates at the shot noise limit at frequencies above 20 MHz. Therefore, we could operate our receiver at 50 ns intervals, given that our security proofs for CV QKD with a finite constellation hold under the assumption that LO power will fluctuation symbol to symbol. Second, we have identified a new laser from RIO (http://www.rio-inc.com/), with shot noise

limited performance extending down to the 200 kHz range (stated by the vendor). We are getting a demo unit of this laser to validate this for ourselves, and if it works as claimed, we may purchase this laser under SeaKey to continue experimenting.

- **Variable optical attenuator**
    - **Issue:** We tried several "off the shelf" attenuator schemes. Electronic schemes seemed to introduce excess noise into the amplitude of one arm of the homodyne receiver. Mechanical solutions for variable attenuation did not provide the attenuation precision necessary to achieve -30 dB of common mode rejection ratio.
    - ***Remedy***: Using parts adapted for the fiber-bench approach from Thorlabs, we engineered a precision attenuation scheme which incorporates a micrometer rotation mount into the Thorlabs fiber bench, as shown in Figure 2. This allows for precise and stable modulation of attenuation in one arm of the receiver.

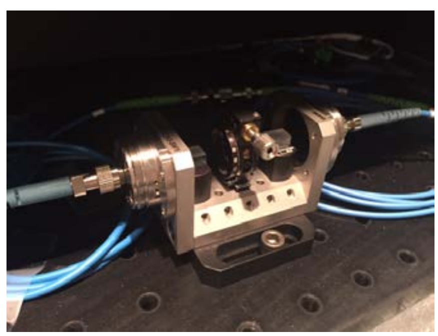


Figure 2 Photograph of our engineered precision attenuator. Left hand and right hand dispersive prims sandwich a half waveplate in a precision rotation stage. The half wave plate, mounted in a micrometer, modulates the attenuation of the light.

Experimentation Techniques:

Our data taking setup is shown in Figure 4. This setup is primarily used to characterize laser noise, as this has been determined to be limiting us from achieving the shot noise limit for our measurements. The fiber-coupled CW laser is sent through fiber to a fast (1 GHz) PIN photodiode (DET01CFC). The output of the detector is sent to an RF amplifier, to amplify the laser signal above the noise floor of the spectrum analyzer used to evaluate the signal. Characteristic shot noise will have a frequency independent power spectral density. It was noted that the Orbits lightwave ethernal laser we have been using thus far, did not have this characteristic until above 20 MHz. A second characteristic of shot noise is the variance of the signal should increase linearly as the laser power increases. We are still validating that above 20 MHz this is true for the ethernal laser, but initial evaluation has determined that this is true.

As mentioned earlier, we have been searching for alternative lasers that have shot noise limited performance at a much lower frequency range, to facilitate data taking. We have identified the RIO Planex laser, and are in the process of getting a demo unit to evaluate its shot noise performance.

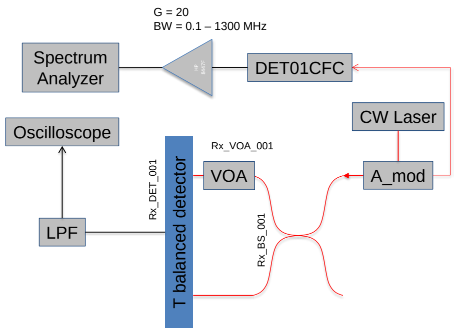


Figure 4 Schematic of our experimental setup to measure laser noise spectrum and homodyne receiver noise.

We have also begun setting up the transmitter for phase encoding coherent states. We have identified the amplitude and phase modulators that will be used to carve coherent state pulses and encode the QPSK states.

Next Steps:

In the next quarter we will:

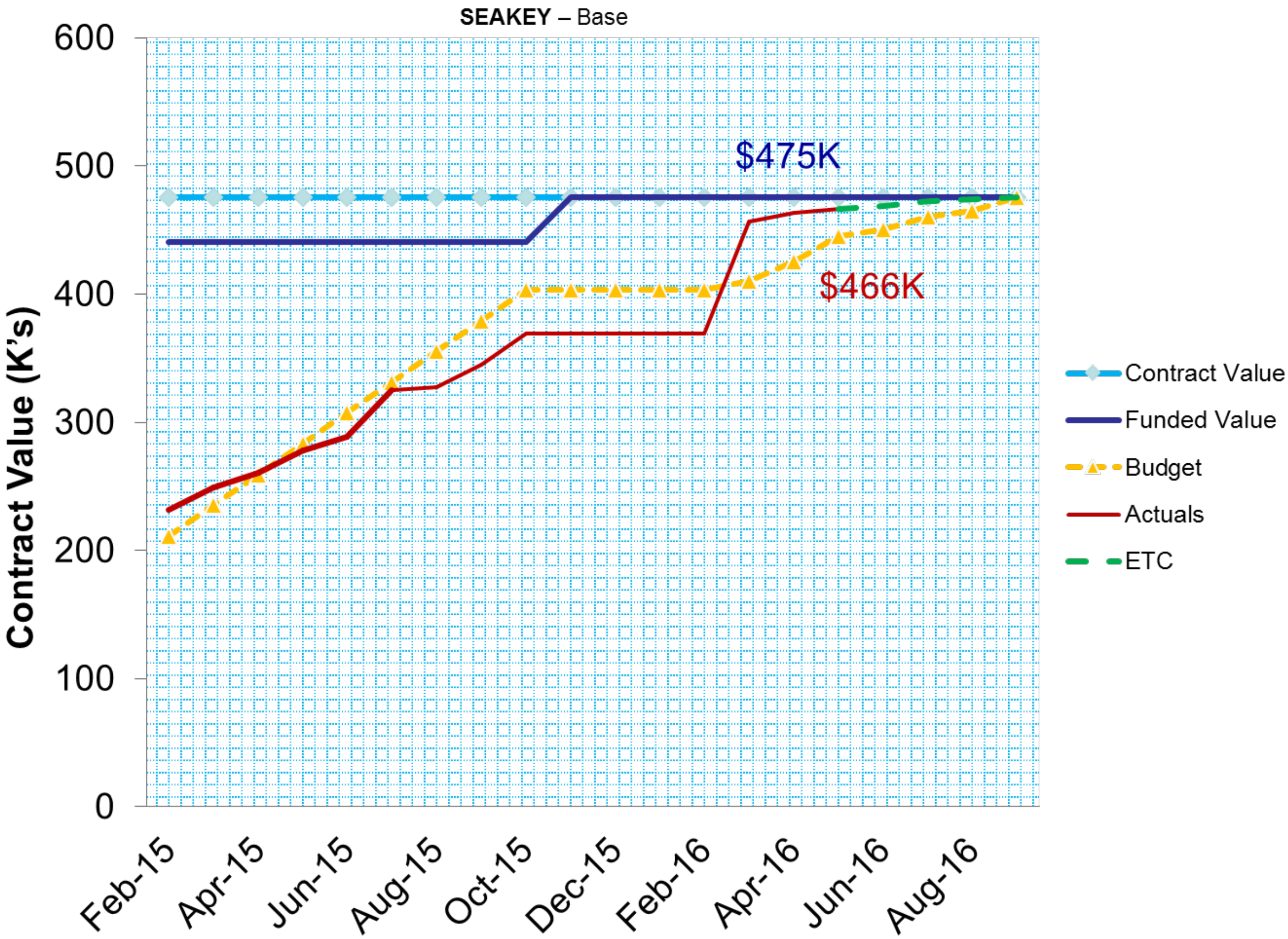
- continue construction of the receiver setup and finalize operation at the shot noise limit – and use this data to determine key rates as a function of distance
- continue construction of the QPSK transmitter.
- Setup and operate the InGaAs camera to evaluate environmental optical noise to plug into key rate calculations

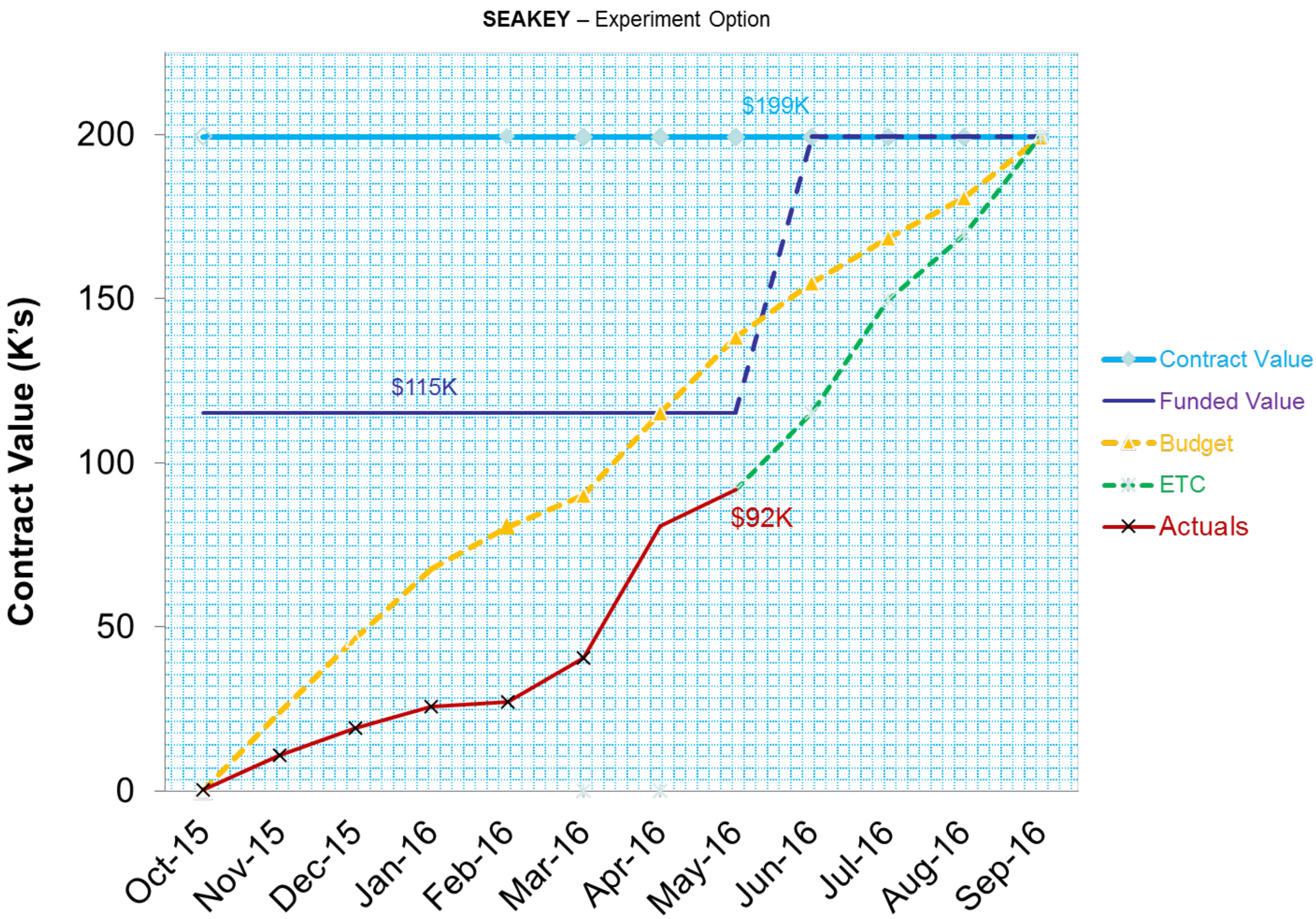
Section C. Problem Areas – Identification

There are no problems or issues to report at this time.

Section D. Financial Update

Financial Charts reflecting Year 2:




SEAKEY – Experiment Option
Contract Value (K's)
200
150
100
50
0
$199K
$115K
$92K
Oct-15
Nov-15
Dec-15
Jan-16
Feb-16
Mar-16
Apr-16
May-16
Jun-16
Jul-16
Aug-16
Sep-16
Contract Value
Funded Value
Budget
ETC
Actuals